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θ^1 and γ Tauri: Understanding the Coronal Structure of Hyades Giants

EUV Spectroscopy of BY Dra Systems NASA Contract NAS5-32640

Combined Final Report

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1. Summary

These programs involve: (1) analysis and interpretation of EUVE spectrometer observations of the active giant β *Cet* in comparison to the Hyades giant θ^1 *Tau* , and (2) analysis and interpretation of EUVE spectrometer observations of the BY Dra systems FK Aqr, DH Leo, and BH Lyn. EUVE carried out observations of β *Cet*, but has yet to perform an observation of θ^1 *Tau*. In β *Cet*, a number of Fe lines from high ionization species were observed, up to Fe XXIV. The spectrum overall resembles that seen in the active binary Capella (α *Aur*).

All three BY Dra systems were observed by EUVE, and show evidence of high-temperature ($\sim 10^7$ K) plasma; FK Aqr and DH Leo show significant variability in their Deep Survey lightcurves. In FK Aqr, spectral differences between its "quiescent" and "active" states suggest possible differences in the plasma density. In DH Leo, the Deep Survey lightcurve, taken over nearly 8 days, shows a distinct period of ~ 1.05 days, similar to the photometric period. The emission measure distributions of all three systems are rather similar in shape, and can be well-represented by a power law with slope ~ 1.5 from 6.2–7.0 in log T.

2. Technical Progress

Over the course of this project, the following work was accomplished:

(1) We obtained EUVE observations of β *Cet* for a net exposure time of ≈ 180 ksec. In collaboration with T. Ayres (U. Colorado), we extracted short (80–170 Å) and medium (150–380 Å) wave spectra. These are shown in Figs. 1 and 2. In addition, we analyzed the Deep Survey (DS) Lexan lightcurve of β *Cet*, taken simultaneously with the spectrometer observation (Fig. 3). The lightcurve showed little change over the ≈ 6 day duration of the observation: the slight downtrend in the count rate over the course of the observation may be real, or may be just the effects of the DS "dead spot". In any event, we may safely place an upper limit to the decline of <20% over the course of the observation. As is evident in the light curve, no flares were detected.

(2) The β *Cet* spectrum shows many high-ionization Fe ion lines, from Fe XV to Fe XXIV, in addition to He II. The strongest line is the Fe XVIII line at $\approx$ 93.8 Å. Unlike the spectra of the BY Dra systems (see below), which show a higher degree of activity as evidenced by the strongest EUV line in their spectra being Fe XXIII (132.8 Å), β *Cet*'s emission measure distribution strongly resembles that of α *Aur* (Capella).

(3) β *Cet* also shows evidence of a strong He II 304 Å line.

(4) We compared the β *Cet* EUVE measurements with HST/GHRS observations taken several months earlier. The results of this comparison were presented at the January 1995 American Astronomical Society meeting in Tucson, AZ. The abstract is attached to this report.

(5) We obtained EUVE observations of the BY Dra systems FK Aqr, DH Leo, and BH Lyn. In addition to the EUVE spectrometer data, we analyzed the DS/Lexan lightcurves for all three systems. Two systems, FK Aqr and DH Leo, showed significant variability. FK Aqr appeared to change from a "low state" to a "high state" in the middle of the observation. Line ratio analysis of Fe XXII density sensitive lines suggested a change in density accompanied this change in EUV luminosity, with a higher density in the *low* state. DH Leo exhibited a periodicity of $\approx$ 1.05 days, consistent with its photometric period.

(6) The spectra of the three BY dra systems were generally rather similar (except for the overall flux). A DEM analysis indicated that they all had similar shapes as well, corresponding to a power law of slope $\approx$1.5 from 6.2–7.0 in log T.

(7) The results of the BY Dra analyses were presented at IAU Colloquium No. 152, "Astrophysics in the Extreme Ultraviolet", Berkeley, CA. A copy of the contribution to the proceedings is attached to this report.

3. Presentations and Publications

- "HST/GHRS and EUVE Spectra of the Active Clump Giant β Ceti (KO III)," T.R. Ayres, A. Brown, S. Drake, T. Simon, R.A. Stern, and B.E. Wood, 1994, B.A.A.S., 26, 1380.
- "EUVE Observations of BY Dra Systems," R.A. Stern and J.J. Drake, 1995, in proceedings IAU Colloquium No. 152, *Astrophysics in the Extreme Ultraviolet*, eds. S. Bowyer, R. Malina, B. Haisch.

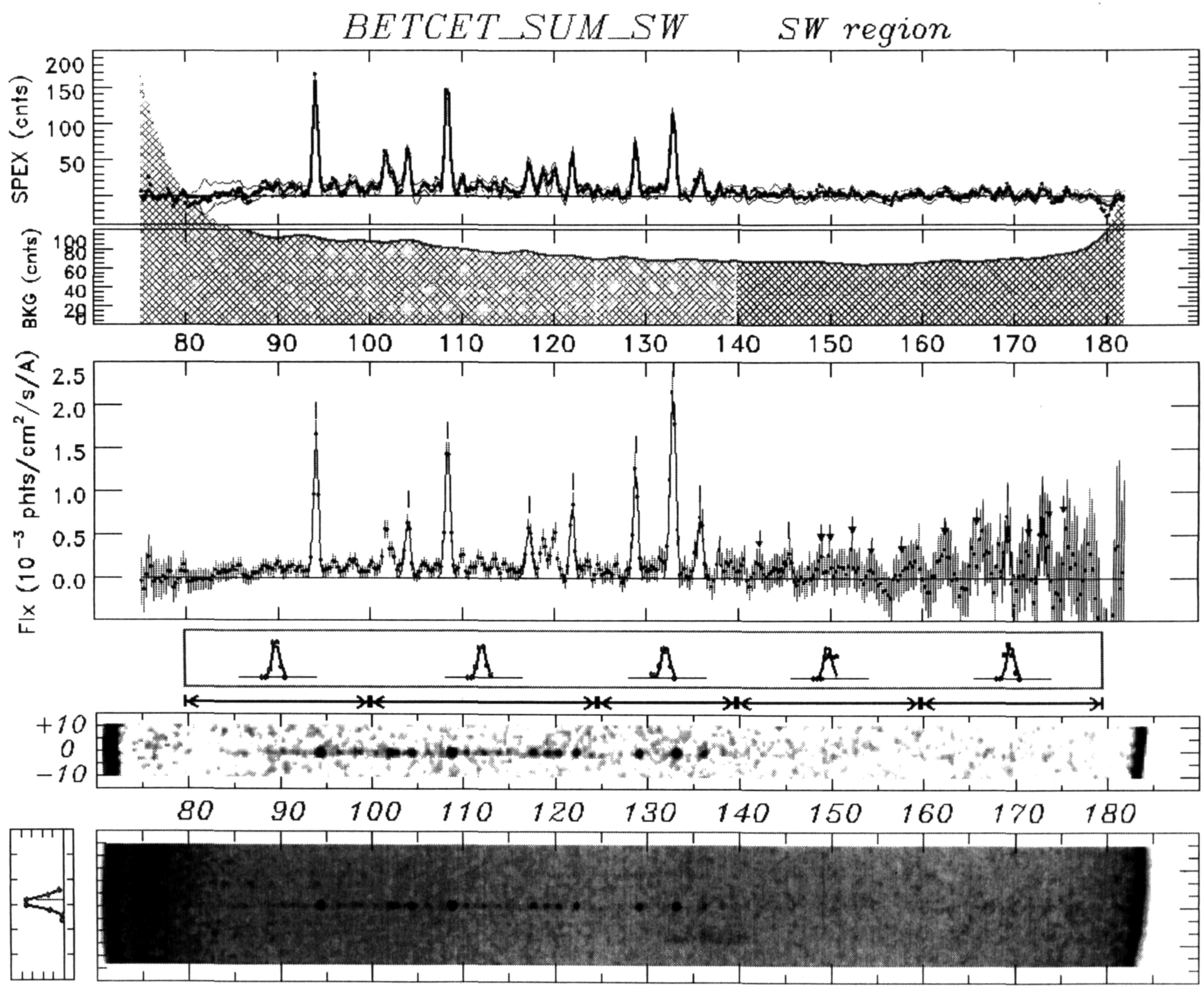
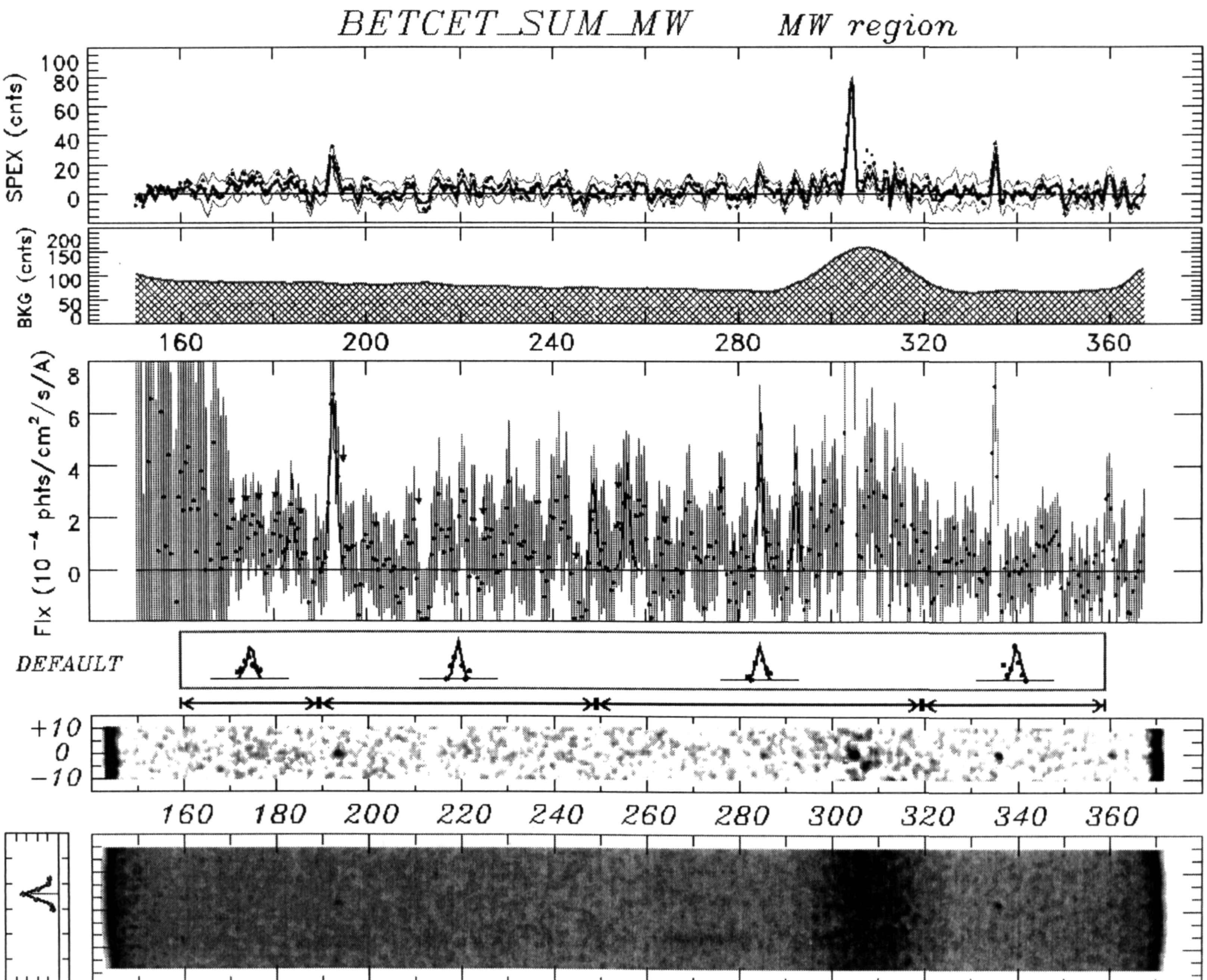


FIG 1



BETCET_SUM_MW
MW region
SPEX (cnts)
BKG (cnts)
Flx (10^-4 phts/cm^2/s/A)
DEFAULT

FIG 2

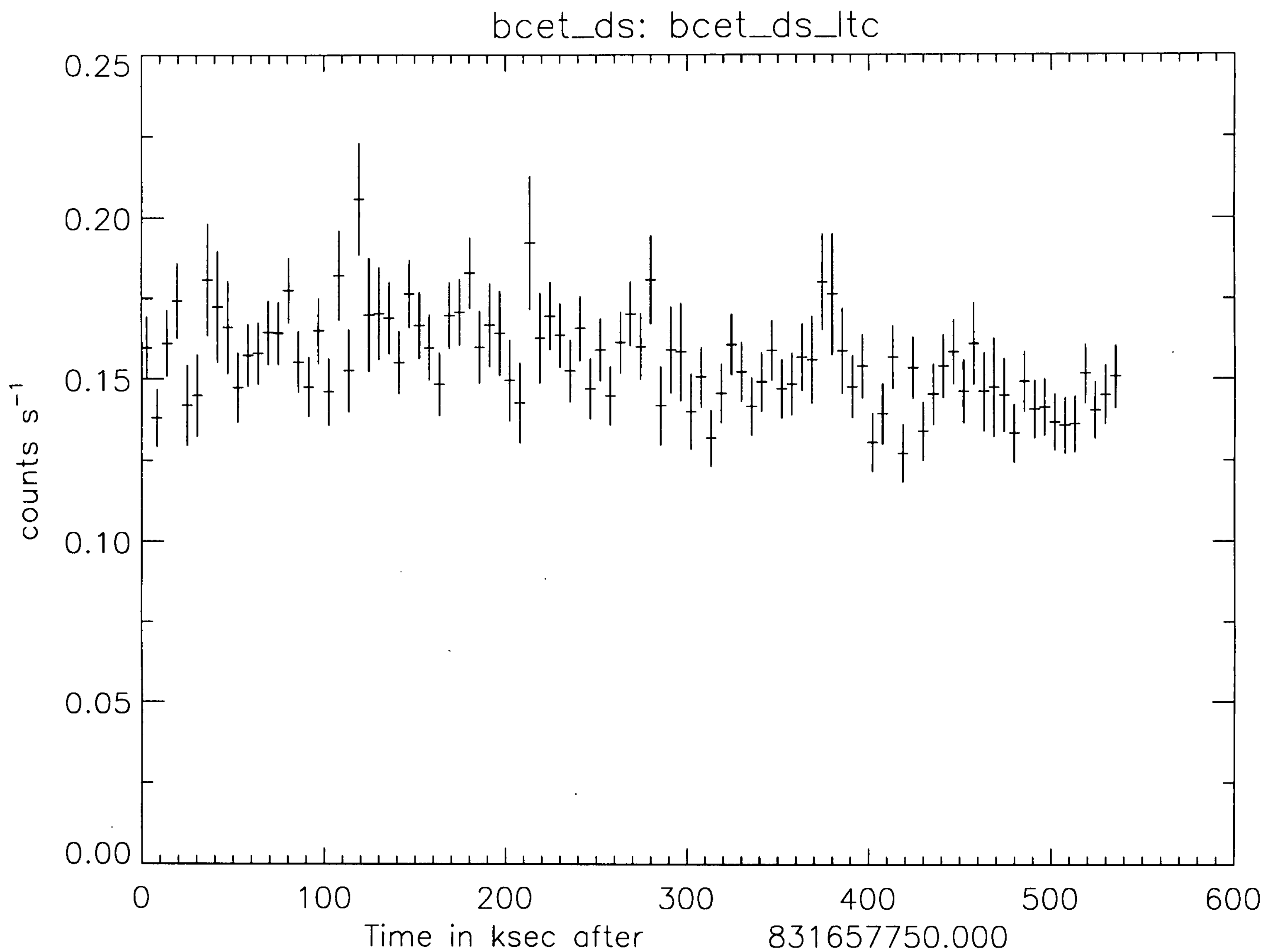

bcet_ds: bcet_ds_ltc
0.25
0.20
0.15
0.10
0.05
0.00
counts s^{-1}
0
100
200
300
400
500
600
Time in ksec after 831657750.000

FIG 3

HST/GHRS and EUVE Spectra of the Active Clump Giant β Ceti (K0 III)

T.R.Ayres, A.Brown (CASA/U.Colorado), S.Drake (GSFC), T.Simon (IfA/U.Hawaii), R.A.Stern (LPARL)

The nearby red giant β Ceti (HD 4128: K0 III; d = 16 pc) is in the postflash core-helium burning phase. It is a member of a class of coronally active "Clump" giants that includes the G8 primary of Capella (α Aur: G8 III + G0 III) and the Hyad θ^1 Tauri (K0 III). Prior to the first ascent of the giant branch, such stars very likely were hyperactive Hertzsprung-gap giants, like the G0 secondary of Capella and 31 Comae (G0 III).

HST/GHRS obtained spectra of β Ceti on 1994 June 2, recording five spectral intervals using both the SSA and LSA. Exposure times ranged from 5.4 minutes (ECH-B/SSA at 2800 Å) to 43.5 minutes (G160M at 1400 Å). Strong emissions of H I, Mg II, Si III, Si IV, C IV, and N V were obtained with high S/N. Fainter lines of N I, C I, Si I, O IV], and O V] also were seen. After correction for systematic effects, we find that emissions formed below about 3×10^4 K are close to the rest frame of the star, but higher excitation species are systematically *redshifted* (as had been suggested previously on the basis of low S/N IUE echelle spectra). The redshifts peak (+16 km s^{-1}) at C IV temperatures ($\approx 10^5$ K); are about 50% smaller at N V/O IV ($\approx 2 \times 10^5$ K); and a factor of two lower at Si IV ($\approx 6 \times 10^4$ K). The strong high-excitation emissions also show evidence for "broad components" (FWHM $\approx$ 150 km s^{-1}) at the bases of their profiles which are even more redshifted than the parent lines (FWHM $\approx$ 90 km s^{-1}). We see no evidence for wind absorptions in the very high S/N ($> 50:1$) profiles of Mg II k or H I Lyα, although the former displays a clear chromospheric central reversal outside of the sharp ISM feature.

We will compare the HST/GHRS spectra with a 140 ks pointing on β Ceti by the EUVE, conducted during the six day period beginning 1994 September 30.

This work was supported by HST and EUVE GO grants.

Abstract submitted for AAS [AAS] meeting

EUVE Observations of BY Dra Systems

By R. A. STERN[1,3] AND J. J. DRAKE[2]

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We have observed 3 nearby BY Dra systems, FK Aqr, BF Lyn, and DH Leo, with the EUVE spectrometers. All 3 show evidence of high-temperature ($\sim 10^7$ K) plasma; FK Aqr and DH Leo show significant variability in their Deep Survey lightcurves. In FK Aqr, spectral differences between its "quiescent" and "active" states suggest possible differences in the plasma density. In DH Leo, the Deep Survey lightcurve, taken over nearly 8 days, shows a distinct period of $\sim$ 1.05 days, consistent with the photometric period. The emission measure distributions of all three systems are rather similar in shape, and can be well-represented by a power law with slope $\sim$ 1.5 from 6.2–7.0 in log T.

1. Introduction

The BY Draconis stars are a group of red (dKe–dMe) low-amplitude variables with photometric periods of typically a few days, Ca II and often Hα emission, and unusually bright X-ray emission for their spectral type, with a typical $L_x \approx 5 \times 10^{29}$ erg s^{-1} (Bopp and Fekel 1977, Caillault 1982). Most, but not all, are binaries in short period (few days) orbits, with rapid rotation the crucial factor in their high level of activity. A few are dMe flare stars (Bopp and Fekel 1977, Strassmeier *et al.* 1988). From the results of EUV sky surveys (Pounds *et al.* 1993, Bowyer *et al.* 1994), it now appears that many of the BY Dra systems are strong EUV emitters as well: these include KZ And, FK Aqr, V1396 Cyg, V775 Her, DH Leo, BF Lyn, YY Gem, V833 Tau, CC Eri, and BY Dra, the prototypical system. All of these systems are within $\approx$ 30 pc of the Sun. Because they are relatively young main sequence stars, with X-ray activity levels typically 10^2 or more times solar, they represent some of our most accessible main sequence stellar laboratories in the EUV with which to examine the effect of strong magnetic heating on coronal temperature. We have performed a detailed study of 3 representative, nearby, EUV-bright BY Dra systems: FK Aqr, DH Leo, and BF Lyn. The characteristics of these systems are listed in Table 1. The column densities (N_H) to these systems are uncertain, but are probably $\lesssim$ 1–2 $\times$ 10^{18} cm^{-2}.

2. The FK Aqr Lightcurves

The Deep Survey (DS) telescope feeds both an imaging detector and the 3 EUVE spectrometers (Bowyer and Malina 1991), thus providing simultaneous photometry and spectrophotometry. Sources near telescope boresight are imaged in the DS/Lexan band (70-180 Å). In Figure 1 we show the lightcurves obtained in DS/Lexan and by summing the 80-140 Å region in the SW spectrometer. The data are binned over $\approx$ 1 satellite orbit, with $\sim$ 2 ksec effective exposure time in each bin. The light curves are quite similar (the DS/Lexan has smaller errors due to the higher count rate), even to extent of recording a brief flare at $\sim$ 135 ksec into the observation. The most striking aspect of the lightcurves is the dramatic rise in EUV flux at $\sim$ 220 ksec into the observation. Since

Star	Sp. Type	P_{orb}	d (pc)	Lex/B	Al/C
FK Aqr	dM2e/dM2e	4.08	7.7	150	50
BF Lyn	K2 V/dK	3.8	29	90	50
DH Leo	K0/K7/K5	1.07	33	50	40

TABLE 1. BY Dra Systems Observed (Lex/B and Al/C are EUVE scanner count rates/ksec)

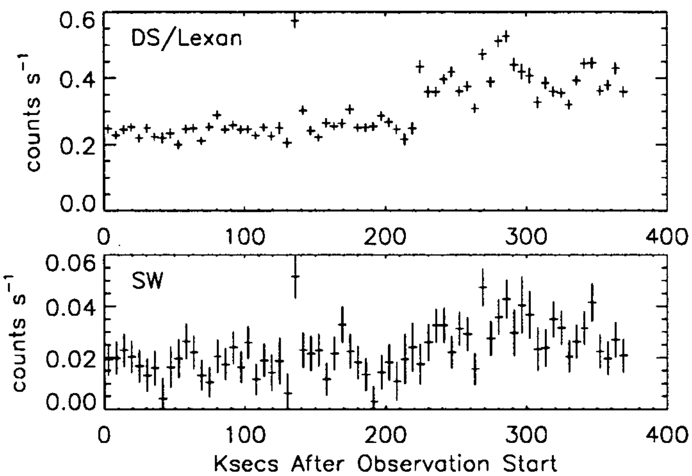

FIGURE 1. Deep Survey/Lexan (40–190Å) lightcurve for FK Aqr (top); Summed SW spectrometer (80–140 Å) lightcurve (bottom). Each data point covers about 1 spacecraft orbit (96 mins.)

FK Aqr is not an eclipsing system, we may attribute this rise either to rapid growth of a large active region or complex of active regions, or perhaps to the rotation of an already existing active region complex onto the visible disk of one of the stars in the system. Since the length of the observation ($\approx$ 4.28 d) is slightly longer than the orbital period (4.08 d), but slightly shorter than the photometric period (4.39 d), we canot rule out either explanation or a combination of both.

3. The FK Aqr Spectra

Given the appearance of "quiescent" and "active" states in the FK Aqr lightcurve, we have extracted EUVE short wavelength and medium wavelength spectra in two parts: one including the period before the lightcurve "transition" (but excluding the flare at 135 ksec), and a second part including both the flare and the time period after the transition. These are shown in Figure 2. The most noticeable differences between the spectra are the relative strengths of the Fe XXI 128.7 Å line compared to the other Fe XXI line and lines from nearby ionization stages. This could be an indicator of higher ($\sim 10^{13}$ cm^{-3}) densities; however, an independent confirmation through the Fe XXII density-sensitive 117/114 line ratio is problematic because of the lower statistical significance of these line fluxes.

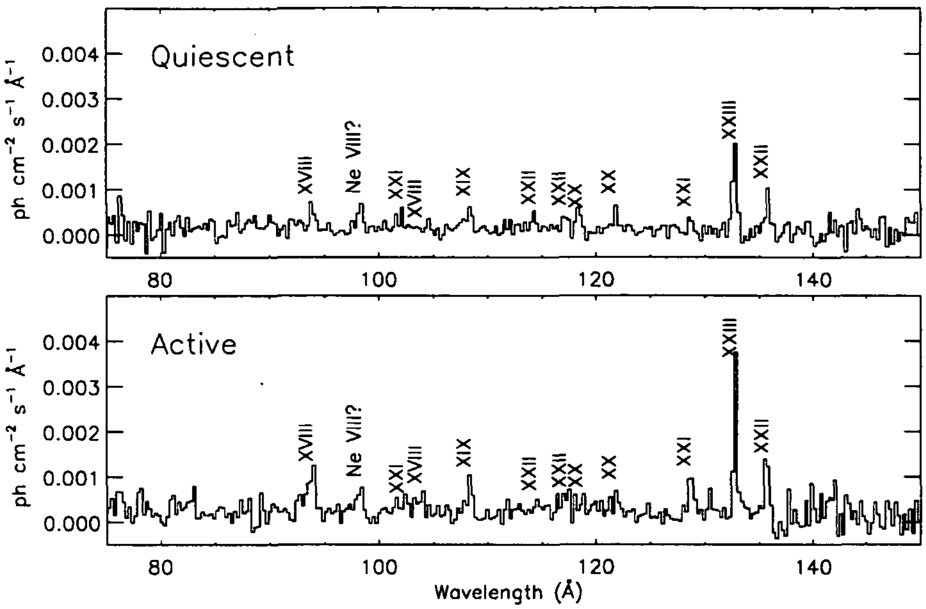

FIGURE 2. Quiescent (top) and active (bottom) SW spectra for FK Aqr. The data have been rebinned by a factor of 4 to about 0.26 A. The effective exposure times are 74 and 54 ksec, respectively. In each plot, the ionization stage of Fe for each line is indicated.

4. DH Leo

4.1. *The Lightcurve: Rotational Modulation?*

Our observation of DH Leo covered a time span of $\approx$ 670 ksec, or over 7 binary or photometric periods. The DS/Lexan lightcurve for this observation is shown in Figure 3, along with a periodogram analysis (using the "fast" algorithm of Press and Rybicki 1989). The most significant peak occurs at a period of $\approx$ 1.05 days. Because this period is close to $\sim$ 1 day as well as the photometric period of 1.067 days (Barden *et al.* 1986), we also performed a periodogram analysis of the detector background, but failed to find a significant peak at either of these values. Thus, for the moment we conclude that the periodicity is real, and is close enough (within an estimated error of $\pm$0.05 d) that we may associate it with the photometric period of DH Leo. A phased lightcurve at this period is shown in Figure 4, indicating a definite "ripple" in the EUV flux. No other obvious periodicity in the EUVE satellite at $\sim$ 1 day is known to produce such a variation in the source count rate, thus we tentatively conclude that our lightcurve is an indication of rotational modulation in the DH Leo system.

4.2. *Spectrum*

Dividing up the DH Leo spectrum by phase into "low level" and "high level" count rate did not produce significant spectral differences, unlike in the case of FK Aqr. The relative strengths of the Fe XXII 117/114 line ratio are consistent with the low-density limit (i.e. $\lesssim 10^{12}$ cm^{-3}).

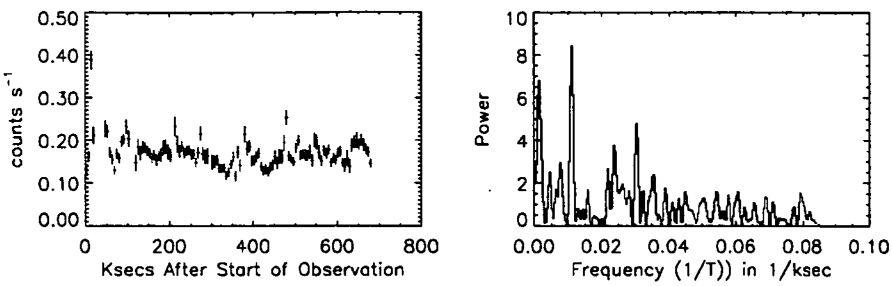

FIGURE 3. DS/Lexan lightcurve for DH Leo (left) and periodogram analysis (right)

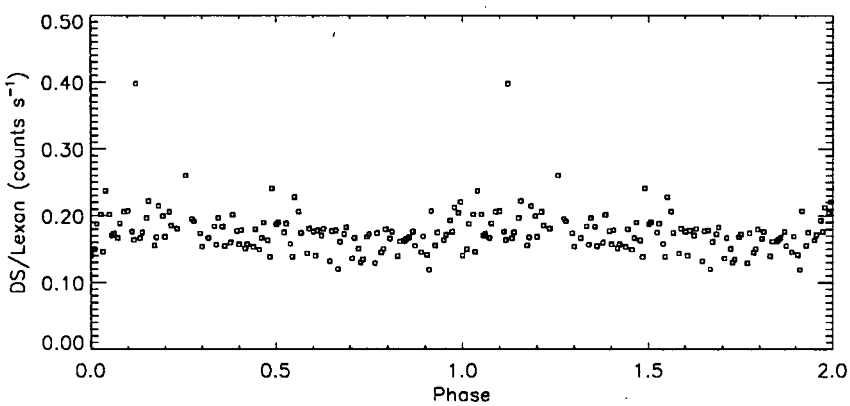

FIGURE 4. Phased lightcurve for DH Leo (phase = 0. has been arbitrarily chosen at the start of the observation)

5. The BF Lyn Lightcurve and Spectrum

The BF Lyn DS/Lexan lightcurve exhibited variability of up to 50% during the course of the observation ($\approx$ 2.5 d). Since the total observation coverage extends for less than a single orbital or photometric period of the system (3.8 days), the remaining variability is probably due to a combination of flares, rotational modulation, or growth and decay of active regions. BF Lyn is a relatively weak EUV source, and the 70 ksec effective exposure time reveals fewer lines (many at low significance) than the other 2 BY Dra systems. However, the Fe XXIII/XX feature is prominent, and other ionization stages from XV - XXII are also present, thus indicating a relatively hot corona.

6. Emission Measure Distributions

In Figure 5 we show preliminary emission measure distributions for the BY Dra systems. These have been computed using the Fe emissivities of Brickhouse *et al.* (1995), and the "Pottasch" method of using the peak temperature of the emissivity function. As such they represent a quick estimate of the form of the EM distribution; further analysis using spectral synthesis methods may yield a better estimate of the EM. Note that overall shapes of the EM distributions are quite similar for all the systems, and in the range log T = 6.2–7.0, can be well approximated by a power law of slope $\sim$ 1.5. DH

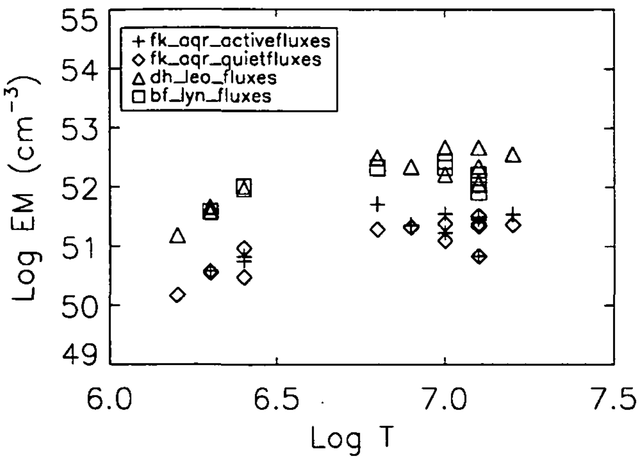

FIGURE 5. Emission measure distributions for the BY Dra systems (see text)

Leo, the shortest period system, also appears to have the greatest quantity of the highest temperature material. Even allowing for the scatter in the plot due to a combination of statistical uncertainties (up to a factor of 2 for the weaker lines), and atomic physics uncertainties, the enhancement in the EM at log T $\sim$ 6.8 as seen in the Fe XVIII 93.9 Å line for the "active" FK Aqr spectrum is still quite significant, and somewhat reminiscent of the "bump" seen in the Capella EM distribution in Dupree *et al.* (1993) and Brickhouse *et al.* (1995). We note that deriving the EM for the quiescent spectrum assuming $n_e = 10^{13}$ cm^{-3} made only a slight difference in the EM distribution.

7. Summary

EUVE observations provide one of the best ways to study both the variability and the temperature structure of the coronae of BY Dra systems. Both periodic modulations and stochastic variability are amply evident in the short wavelength high temperature lines seen by EUVE: the DH Leo study for over 7 binary orbits is probably the best example to date of rotational modulation of stellar coronal emission. In addition, there is a hint of a high density structure in the *quiescent* corona of FK Aqr as compared to the "active" or flaring corona.

R.A.S. wishes to thank the scientists and staff of the Center for EUV Astrophysics for making his stay there enjoyable and productive. R.A.S. was supported in part by NASA contract NAS5-32640 and by the Lockheed Independent Research Program. J.J.D. was supported by NASA Grant AST91-15090.

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13. ABSTRACT *(Maximum 200 words)*

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